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► **To cite this version:**

M. Yu. Tikhomirov, Y. M. Spalek, V. I. Lebedynskiy. A Silicon Integral Transducer with an Extended Operating Temperature Range. 1991. hal-04160942

**HAL Id: hal-04160942**

**<https://hal.science/hal-04160942v1>**

Preprint submitted on 13 Jul 2023

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# A Silicon Integral Transducer with an Extended Operating Temperature Range

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The data were written in 1991

## Abstract

This paper discusses technical solutions for creating a silicon integral transducer with distributed circuit parameters without p-n junctions with an extended operating temperature range. The data presented relate to the field of semiconductor devices and can be used in the production of high-precision semiconductor sensors of physical quantities for operation in a wide temperature range, such as in the measurement of pressure differential transmitters.

## 1 Field of study

The data presented are related to the field of semiconductor devices and can be used in the manufacture of high-precision semiconductor transducers in physical quantities for operation in a wide temperature range.

To convert the strain of an elastic element into an electrical signal, a DC bridge measurement circuit consisting of four piezoresistors is used <sup>1</sup>.

The conversion characteristic of such a circuit is determined by the transfer function  $k$ , whose dependence on temperature and strain changes the resistance of the piezoresistors, according to <sup>2</sup> is represented in the form:

$$k = K_0(T) + K(\varepsilon_y; T) \cdot \varepsilon_y, \quad (1)$$

where  $K_0(T)$  is the normalized null output of the measuring circuit in the absence of the mechanical input quantity;  $K(\varepsilon_y; T)$  - the strain sensitivity coefficient of the transducer.

The error of silicon integrated resistor transducers can be reduced by bringing the value and temperature dependence of the normalized null output close to zero in the case of fulfilling the requirements to the manufacturing technology and design, among which are:

- in a certain temperature range, minimizing the deviation of resistivity of resistors from the average values and identical behavior of the characteristics of resistors;
- minimization of the values and scatters of the initial deformations in the elastic element in the areas of strain gauge placement plus identical behavior of the characteristics of these values in a certain temperature range;
- the equality of all thermal resistances in the channels of the heat sinks: 'piezoresistor - elastic element - sensor body.'
- minimizing of the temperature gradient in the plane of the piezoresistors on the elastic element.

These requirements are fulfilled in the two known topological solutions for the symmetric four-branch bridge circuit:

- Four single-band piezoresistive channels of longitudinal and transverse piezoresistors interconnect the square contact areas, centered at the vertices of the square;
- Similarly to the Hall transducer, four contact areas are located in the area of the piezoresistive sensing element.

## 2 Overall Information about Silicon Integrated Transducers for Operation in a Wide Temperature Range

There is a known method for manufacturing a converter with symmetric bridge circuit<sup>3</sup>. Chemical etching methods on an insulating substrate create a silicon mesastructure of the bridge circuit, which contains square contact pads in the vertices, interconnected by single-band piezoresistive channels. Representatives of the known method are technical solutions:

- sensor with a heteroepitaxial silicon bridge circuit on a monocrystalline sapphire elastic element;
- sensor with monocrystalline (or polycrystalline) silicon bridge circuit recessed in a layer of glass or other dielectric formed on a silicon elastic element.

The general disadvantage of the above methods is the difficulty in accurately reproducing the small thickness of the elastic element in the production of miniature sensors: in the first case, due to the need for high-temperature gas profiling with  $\alpha\text{-Al}_2\text{O}_3$  in the second case, the non-reproducibility of the geometric dimensions of the dielectric layer in the sintering process. The disadvantage of the method for the second solution is also that the low values of the modulus of elasticity of materials, used as dielectrics, significantly limit the operating range of conversion of the mechanical value.

The next common disadvantage is the occurrence of mechanical stresses in silicon strain gauges as a result of the mismatch between the structure of the substrate or the insulating layer and the structure of single-crystal silicon. In the first case, a cubic silicon lattice structure is grown on a sapphire modification  $\alpha$  with a hexagonal lattice, and in the second case, an amorphous glass structure is used. These stresses, resulting from the mismatch of thermal expansion coefficients, are temperature dependent and lead to the following issues.

- A basic static error caused by strain in the elastic element under normal conditions, along with a complementary temperature error.
- An additional constraint on the correlation values of the thicknesses of the elastic element, insulation, and mesa resistors.

The articles<sup>4 5</sup> describe a method of manufacturing a mechanically sized silicon integrated transducer with a "shear" piezoresistive sensing element, which is a piezo analogue of the Hall transducer (X-ducer). In n-type silicon wafers with crystallographic orientation in the plane (100), a p-type sensing element region is formed by diffusion doping. On the orthogonal axes, two pairs of contacts are created within the area.

In mechanical quantity measurements, a direct current passing through the longitudinal axis of the element generates a strain-dependent potential difference on a pair of contacts located on the transverse axis. The advantage of the known method, consisting of reducing the value of the normalized null output and its temperature dependence, does not lead to a significant decrease in the additive component of the complementary temperature error, since the strain sensitivity of the "shear" strain gauge elements is 2-3 times less than the strain sensitivity of a single-band strain gauge channel in the full bridge circuit.<sup>6</sup>

The second disadvantage of the method is that the operating temperature range for such converters is limited to  $+100^\circ\text{C}$ . The boundary temperature is determined by the diffusion component of the reverse current which grows strongly at these temperatures and is proportional to the surface area of the p-n junction that insulates the sensor from the elastic element.

The disadvantage is that the small input resistance of the 'shear' strain gauge sensing element does not allow the use of a significant voltage for its power supply, and the use of a low-resistance material sharply worsens the temperature characteristics of the sensor.

A method for manufacturing resistance silicon mechanical transducers is also known<sup>7</sup>. We will call this RMT. The resistor full-bridge circuit contains four contact pads located on the vertices of the square and connected by single-band piezoresistive channels. Piezoresistive channels and

contact pads are formed in the silicon wafer body by doping with an impurity that increases the concentration of minority carriers to form an insulating p-n junction. The resilient element and the rigid base regions are formed by selective chemical etching on the reverse side of the wafer relative to the circuit.

The sensor design drawing (see Fig. 4 in <sup>7</sup>) does not specify the type of isolation of the bridge circuit from the elastic element. Thus, the following variants are expected to be possible for the RMT: isolating the  $p - n$  junction and the non-isolating junction, when the piezoresistors and the elastic element have the same type of conductivity.

Characteristics of the converter are determined by the design parameters under the conditions of electrical isolation of the bridge circuit relative to the elastic element and the rigid base. For this purpose, the surface resistance of the doped layers, the depth of etching and the resistivity of the silicon wafer must provide conductivity in the layers of the bridge circuit at least 10 times higher than in the body of the elastic element.

The limitations imposed on the design parameters are as follows:

$$\frac{1}{10 \cdot R_{bc}} \geq \frac{1}{R_{ee}} \quad (2)$$

where  $R_{bc}$  is the input resistance of the bridge circuit, and  $R_{ee}$  is the resistance of the elastic element between the contacts at the input of the bridge circuit. Conditions (2) must be satisfied throughout the operating temperature range of the transmitter.

Let us estimate the resistivity values for the silicon piezoresistor of the bridge circuit, denoted as  $\tilde{\rho}_{bc}$ , and the elastic element, denoted as  $\tilde{\rho}_{ee}$ , in order to satisfy the relation (2).

For evaluation, we will assume that the elastic element is a flat plate with a thickness of  $H_{ee}$ . Typically, the value of  $H_{ee}$  ranges from  $3 \times 10^{-3}$  cm to  $3 \times 10^{-2}$  cm.

To calculate the input resistance  $R_{in}$  for a parallel connected bridge circuit 52 with a square portion of the elastic element 54, we need to consider common contact pads 55 and 57 <sup>7</sup>.

The electrical resistance of the square section between the contact pads can only be determined by numerical calculations, taking into account their geometrical dimensions. For the calculation, let us assume the following relative sizes: square  $1 \times 1$  and contacts  $0.2 \times 0.2$ .

The resistance of the square section of the elastic element between the contact pads 55-57 (see <sup>7</sup>) can be calculated using the following equation:

$$R_{ee} = 1.383 \cdot \frac{\rho_{ee}}{H_{ee}} \quad (3)$$

Here,  $\rho_{ee}$  represents the resistivity of the silicon elastic element, and  $H_{ee}$  is the thickness of the elastic element.

Let us assume that the number of squares in any resistor channel of the bridge circuit between the boundaries of contacts is 10. This implies that the relative width of the resistor is 0.06.

The resistance of the isolated bridge circuit can be determined as follows:

$$R_{bc} = 10 \cdot \frac{\tilde{\rho}_{bc}}{X_j} \quad (4)$$

Here,  $\tilde{\rho}_{bc}$  denotes the average volumetric resistivity of the piezoresistor channel and  $X_j$  represents the thickness of the piezoresistor channel at which  $\tilde{\rho}_{bc}$  was averaged.

If we take the characteristic value for the thickness of the ion alloy piezoresistor as  $X_j = (0.33 \times 10^{-4} \div 0.36 \times 10^{-4})$  cm and  $H_{ee} = (3 \times 10^{-3} \div 3 \times 10^{-2})$  cm for the thickness of the elastic element, the restrictions can be expressed as:

$$\rho_{ee} \approx (0.63 \div 6.3) \times 10^3 \cdot \tilde{\rho}_{bc} \quad (5)$$

The smallest value of  $\tilde{\rho}_{bc}$  for ion-alloyed silicon piezoresistors appears to be  $\tilde{\rho}_{bc} = 2.8 \times 10^{-3} \Omega \cdot \text{cm}$ .

In this case, the input resistance of the bridge circuit configured in <sup>7</sup>, with the piezoresistors 51 isolated from the elastic element, will be  $R_{bc} = 800 \Omega$ . Therefore, to vary the thickness of the elastic element within the range of  $3 \times 10^{-3} \text{ cm} \leq H_{ee} \leq 3 \times 10^{-2} \text{ cm}$ , the resistivity of silicon  $\rho_{ee}$  must satisfy  $\rho \geq 18 \Omega \cdot \text{cm}$ .

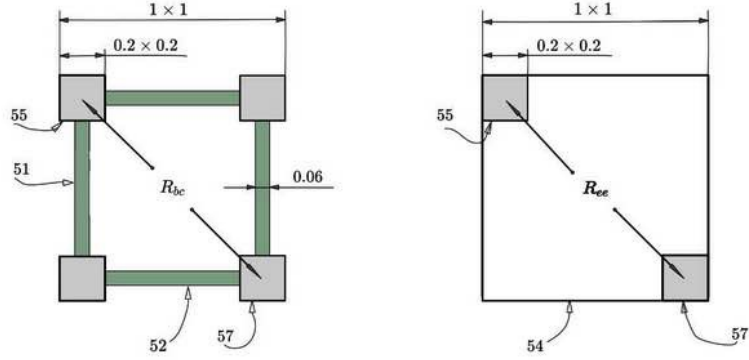


Figure 1: Configurations of the bridge circuit layers and elastic element in Fig.4 *in*<sup>7</sup>

Next, we estimate the critical temperature  $T_{int}$  at which the impurity semiconductor of the elastic element will become intrinsic. At this transformation, the condition  $\frac{1}{10 \cdot R_{bc}} \geq \frac{1}{R_{ee}}$  will certainly be violated due to a sharp increase in the electrical conductivity of the high-resistance elastic element.

We will use the expression given in <sup>8</sup> on page 41 for this estimation:

$$T_{int}(\rho) = 273 \left( \frac{10}{4.5 + \log \rho} - 1 \right) \quad (6)$$

By substituting  $\rho = 18 \Omega \cdot \text{cm}$ , we find the following.

$$T_{int}(\rho = 18 \Omega \cdot \text{cm}) = 200^\circ\text{C} \quad (7)$$

Thus, the upper limit of the operating temperature range for this transducer, when the piezoresistors of the bridge circuit are not isolated by a p-n junction, cannot exceed  $+200^\circ\text{C}$ .

In the case where the piezoresistors are isolated from the elastic element by a p-n junction, the upper limit of the temperature range of the transducer is limited by the leakage current through the p-n junction in the reverse-biased mode. Its value, in reverse bias mode, is determined by the ratio  $I_{rev} \leq 1 \times 10^{-1} \cdot \frac{V_{in}}{R_{in}}$ .

According to our estimation, for example, at  $V_{in} = 5 \text{ V}$ , the leakage current should be  $6.26 \times 10^{-4} \text{ A}$ . At this current value, the change in the sensitivity of the transducer, i.e. the error, will reach 10%

The value of the current at which the change in sensitivity will not exceed the specified norm in <sup>9</sup> is determined by the equation:

$$I_{revN} = 4 \times 10^{-4} \times \frac{V_{in}}{R_{in}} = 4 \times 10^{-4} \times \frac{5}{800} = 2.5 \times 10^{-6} \text{ A} \quad (8)$$

If the current is further increased, the shunt effect of the resistive part of the elastic element on one of the arms of the bridge circuit can cause a change in the transfer ratio value of more than 1% relative to its nominal value.

To estimate the sensor in <sup>7</sup>, we will consider the following dimensions for the bridge circuit in Figure 1: piezoresistor width  $3 \times 10^{-3} \text{ cm}$ , piezoresistor length  $3 \times 10^{-2} \text{ cm}$  and contact size  $(1 \times 10^{-2} \times 1 \times 10^{-2}) \text{ cm}^2$ . The p-n junction area is then  $4.36 \times 10^{-4} \text{ cm}^2$ .

To determine the upper limit of the temperature range for the transducer's operation, we will use characteristic values of the leakage current provided in <sup>10</sup>. At the p-n junction area of  $4.36 \times 10^{-4} \text{ cm}^2$  and the room temperature of  $+20^\circ \text{ C}$  (273 K), the current is  $I_{rev0} = 8.2 \times 10^{-13} \text{ A}$ .

Using the formula  $I_{revN} = I_{rev0} \cdot e^{38.13 \cdot \left( \frac{T_{per} - 293}{T_{per}} \right)}$ , we can calculate  $T_{per}$  <sup>10</sup>. The resulting value is  $T_{per} = +208^\circ \text{ C}$ , which is the temperature that limits the operation range for the RMT transducer with an insulating p-n junction.

Considering that the actual area of the bridge piezoresistor circuits is usually larger than the estimated value, the real limiting temperature is unlikely to exceed approximately  $+180^\circ \text{C}$ .

In both cases, a common reason for limiting the operating temperature range is the sharp decrease in the resistance of the elastic element, which is connected in parallel to the input and output of the bridge circuit, at the temperature where intrinsic conductivity begins. This leads to a decrease in sensitivity to the input value according to the equation:

$$V_{\text{out}} = V_{\text{oc}} \frac{R_{ee}}{R_{ee} + R_{bc}} \quad (9)$$

where  $V_{\text{out}}$  is the output signal from the bridge circuit,  $V_{\text{oc}}$  is the open circuit voltage of the bridge circuit, and  $R_{ee}$  is the resistance of the elastic element connected in parallel to the output of the bridge circuit. The sharp drop in temperature dependence determines the upper limit of the transducer operating temperature range<sup>11</sup>.

A common disadvantage of all the considered methods is the additional temperature error of the bridge measuring circuit when supplied with a stabilized voltage, which is largely determined by the temperature coefficient of sensitivity of the piezoresistor. Depending on the impurity concentration, this coefficient varies in the range of  $(0.13 \div 0.3) \% / K$ . This error necessitates additional time-consuming individual adjustment of the transducer.

### 3 Detailed Description of the Silicon Transducer Measuring Bridge Circuit

The objective is to extend the temperature range and reduce the temperature error by effectively redistributing the current of the charge carriers in the channels and the elastic element.

This problem can be solved by the following method of manufacturing a silicon resistance integral mechanical transducer<sup>9</sup>. Doping is carried out with impurities that increase the concentration of majority carriers in the elastic element, and the average resistivity of the elastic element, the depth of doping, and the geometric dimensions of the channel are selected according to the following ratio.

$$\Gamma_{kt} = \sqrt{\frac{1}{n-1} \sum_{i=0}^n \frac{1}{(T_n - T_0)^2} \left\{ \frac{\left[ 2 \frac{X_j \cdot b}{a} + \frac{\tilde{\rho}_{bc0}}{\rho_{ee0}} \Lambda \right] \left[ K_0 + K_1 \frac{T_0}{T_n} + K_2 \left( \frac{T_0}{T_n} \right)^2 \right]}{\left[ 2 \frac{X_j \cdot b}{a} + \frac{\tilde{\rho}_{bc0} [1 + \alpha_{bc}(T_n - T_0) + \beta_{bc}(T_n - T_0)^2]}{\rho_{ee0} [1 + \alpha_{ee}(T_n - T_0) + \beta_{ee}(T_n - T_0)^2]} \right] \cdot \Lambda} \left[ K_0 + K_1 + K_2 \right]} - 1 \right\}^2};$$

$$T_n = T_2 \frac{n-i}{n} + T_1 \frac{i}{n} \quad (10)$$

In the above equations,  $\Gamma_{kt}$  represents the limit value of the permissible temperature error,  $K^{-1}$ ,  $T_1$ , and  $T_2$  are the limit values of the working temperature range,  $K$ ,  $T_n$  represents the temperature values in the selected intervals for the summation,  $T_0$  is the value of the initial temperature within the working range,  $\tilde{\rho}_{bc0}$  is the average value of the resistivity of the channel at  $T_0$ ,  $X_j$  represents the channel doping depth, which is equal to the depth of the p-n junction at the opposite type of plate conductivity,  $a$  and  $b$  are the length and width of the channel, respectively.  $\alpha_{bc}$ ,  $\beta_{bc}$ ,  $\alpha_{ee}$ , and  $\beta_{ee}$  are the approximation coefficients of the temperature dependences of the resistivity of the channel and plate, expressed as a second degree polynomial of the form  $\rho(T) = \rho_0 [1 + \alpha(T - T_0) + \beta(T - T_0)^2]$ ,  $K_0$ ,  $K_1$ ,  $K_2$  are the approximation coefficients of the temperature dependence of the channel strain sensitivity coefficient, expressed as a second degree polynomial of the form  $K(T) = K_0 + K_1 \frac{T_0}{T} + K_2 \left( \frac{T_0}{T} \right)^2$ ,  $n$  is the number of temperature intervals selected for summation, and  $i = 0, 1, \dots, n$  are positive numbers.

The parameter  $\Lambda$ , which represents the redistribution of the current of the charge carriers in the channels and the elastic element, is determined by measuring the values of the input resistance

of the bridge circuit and the resistance of the electrically isolated channel. This parameter can be obtained by solving the equation:

$$\frac{\rho_{eeT1} \left( \frac{1}{R_{bcT1}} - \frac{1}{R_{T1}} \right) + \Lambda \cdot R_{T1} \left( \frac{1}{2R_{bcT1}} - \frac{1}{R_{T1}} \right)}{\rho_{eeT2} \left( \frac{1}{R_{bcT2}} - \frac{1}{R_{T2}} \right) + \Lambda \cdot R_{T2} \left( \frac{1}{2R_{bcT2}} - \frac{1}{R_{T2}} \right)} = \frac{1 + \frac{\Lambda \cdot R_{T1}}{2\rho_{eeT1}}}{1 + \frac{\Lambda \cdot R_{T2}}{2\rho_{eeT2}}} \quad (11)$$

where  $R_{bcT1}, R_{bcT2}$  are values of circuit input resistances at temperatures  $T_1$  and  $T_2$ , respectively ;  $R_{T1}, R_{T2}$ -values of channel resistances at temperatures, respectively  $T_1$  and  $T_2$  ;  $\rho_{eeT1}, \rho_{eeT2}$  are the resistivities values of silicon wafer (i.e., elastic element) at temperatures, respectively  $T_1$  and  $T_2$ .

The difference in the design of the transducer is the electrical connection of the elastic element to the bridge measuring circuit using a junction  $p + -p$  instead of  $p - n$ .

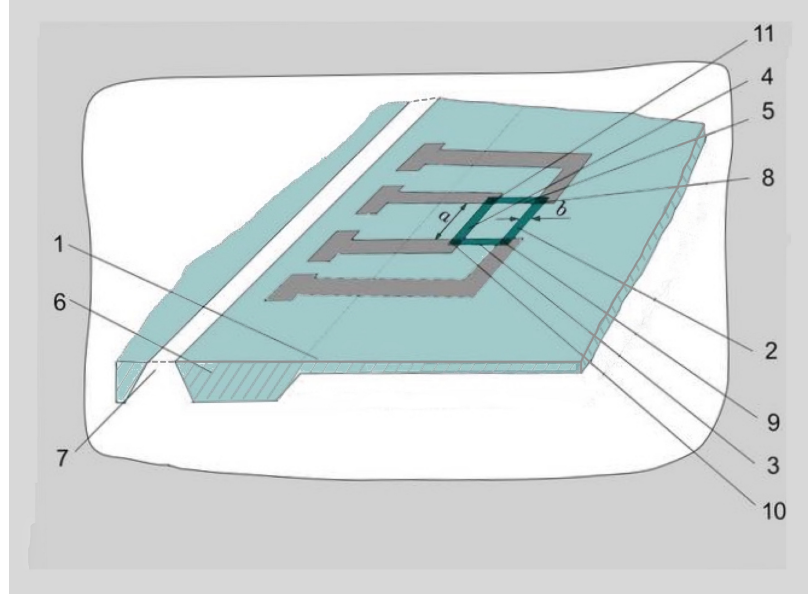


Figure 2: A resistor silicon integral mechanical transducer made according to the proposed method.

The construction of the transducer is explained through the drawings provided. Figure 2 illustrates a silicon piezoresistor transducer for measuring mechanical quantities, manufactured using the proposed method. Figure 3 depicts the structure of the deformation transducer that was modeled using the proposed method. Figure 4 represents a second A-A projection section of the transducer shown in Figure 3. Figure 5 presents an equivalent diagram of the discrete analog model of the transducer shown in Figures 3 and 4.

The fabrication method has the following physical implications:

- Finding a suitable relationship between the electrical characteristics of the elastic element (1) and the piezoresistive channels (2, 3, 4, 5) (sensing elements) that allows for extending the temperature range beyond the critical temperature of the analog. In this case, the temperature dependence of the sensitivity should not exhibit sharp drops.
- Using a parallel-connected section of the silicon elastic element (1) with a positive temperature coefficient of resistance as an element in the compensation circuit for the temperature dependence of the bridge sensitivity when a stabilized voltage is applied.

In the proposed method, the elastic element (1) not only serves as a means to convert mechanical quantities into deformation, but also functions as a component to adjust the temperature dependence of the output signal. The sensor measurement circuit accurately registers changes in ambient temperature, because the elastic element directly transfers heat to the piezoresistive channels 2, 3, 4,

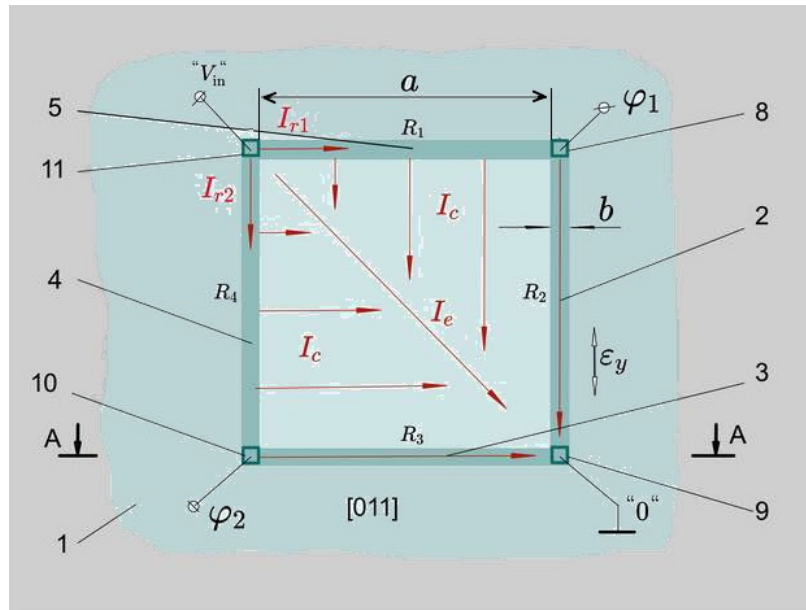


Figure 3: The structure of the selected for modeling characteristics of the deformation transducer.

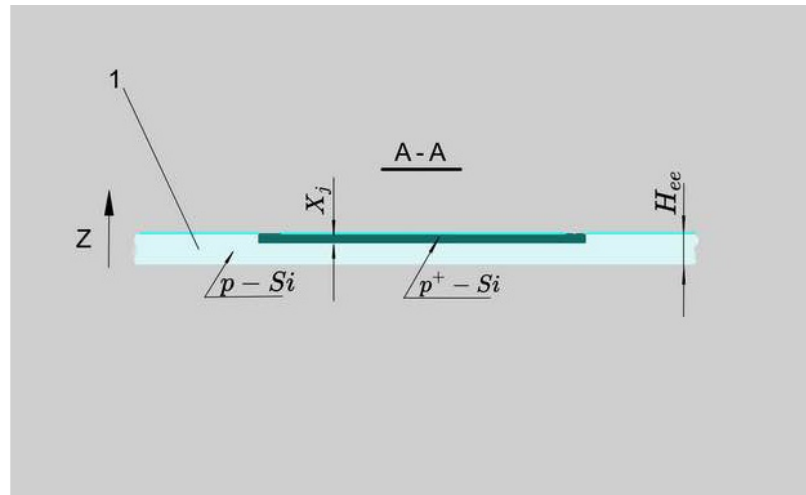


Figure 4: The A-A projection of the section in Figure 3.



5. This manufacturing approach improves the reliability of the transducer (6) at high temperatures (above 200°C) as it does not require additional elements to adjust the characteristics or measurement of the temperature. Failure of the elastic element section (1) is only possible when it undergoes simultaneous mechanical destruction.

The method for determining the parameters of the piezoresistive channels (2, 3, 4, 5) and the elastic element (1) involves measurements and calculations.

For modeling purposes, the authors selected the design of the deformation transducer shown in Figures 3 and 4. This design consists of a silicon elastic element (1) of type p with an orientation in the plane (100) and a thickness of  $H_{ee}$ . The elastic element is connected by four single-band piezoresistive channels (2, 3, 4, 5) of type p+ - oriented along the crystallographic directions [011]. These channels have a width equal to  $b$  and a thickness of  $X$ .

The following conditions and assumptions were made during the modeling process:

- The dimension  $a$  is much greater than the thickness  $H_{ee}$  of the elastic element ( $a \gg H_{ee}$ ).
- The strain component  $\varepsilon_y$  is directed along the crystallographic trajectory [011].
- The bridge circuit is powered by a stabilized voltage source  $V_{in}$  through diagonal contacts 9 and 11.
- The current  $I_r$  is evenly distributed with respect to the cross-sectional plane of channels 2, 3, 4, and 5. Its distribution is identical in adjacent channels 2, 3, and 4, 5, with common contacts, 11, 9, respectively.
- The current in elastic element 1 is evenly distributed across its cross section along the Z direction, which is normal to the flat surface of elastic element 1. Currents are absent outside the circuit area defined by channels 2, 3, 4, and 5. Inside this area, the current is characterized by components  $I_c$  and  $I_e$ . The direction of the component  $I_c$  is normal to the sides of neighboring channels 4 and 5, which share a common power contact 11. The current component  $I_e$  is directed along the diagonal connecting power contacts 9 and 11.
- The distribution of the majority carrier concentration in channels 2, 3, 4, and 5 is assumed to be uniform. The doping level is characterized by the resistivity value, which is equal to the average resistivity when considering the real non-uniform distribution of impurities.  $R_{Sc} = \frac{\rho_{bc}}{X_j}$  represents the surface resistance values of channels 2, 3, 4, and 5 in ohms per square ( $\Omega/\square$ ), and  $X_j$  represents the doping depth of channels 2, 3, 4, and 5 in centimeters, which is equal to the depth of the p-n junction if elastic element 1 is made of silicon of type n.
- The doping level of elastic element 1 is characterized by the resistivity value of the initial material,  $\rho_{ee}$ .

The authors used a discrete analog model of the transducer, represented by an equivalent circuit of a long line with distributed parameters along the X axis, as shown in Figure 5. The differential equations that relate currents and potentials in this model are as follows:

$$\begin{cases} I_{r1}(x) = -\frac{d\varphi_1(x)}{dx} \cdot \frac{b}{R_{Sc1}}; & \begin{cases} I_c(x) = -\frac{dI_{r1}(x)}{dx}; \\ I_c(x) = -\frac{dI_{r2}(x)}{dx}; \end{cases} \\ I_{r2}(x) = -\frac{d\varphi_2(x)}{dx} \cdot \frac{b}{R_{Sc4}}; & \\ I_e(x) = -\frac{dV_{in}(x)}{dx} \cdot \frac{b \cdot H_{ee}}{\sqrt{2} \cdot \rho_{ee}}; & \frac{dI_e(x)}{dx} = 2I_c(x). \end{cases} \quad (12)$$

After transformations, the differential equations can be expressed as:

$$\begin{cases} \frac{d^2\Upsilon_1(x)}{dx^2} = x^{-1}C_1 \cdot \Upsilon_1(x); \\ \frac{d^2\Upsilon_2(x)}{dx^2} = x^{-1}C_2 \cdot \Upsilon_2(x), \end{cases} \quad (13)$$

where:

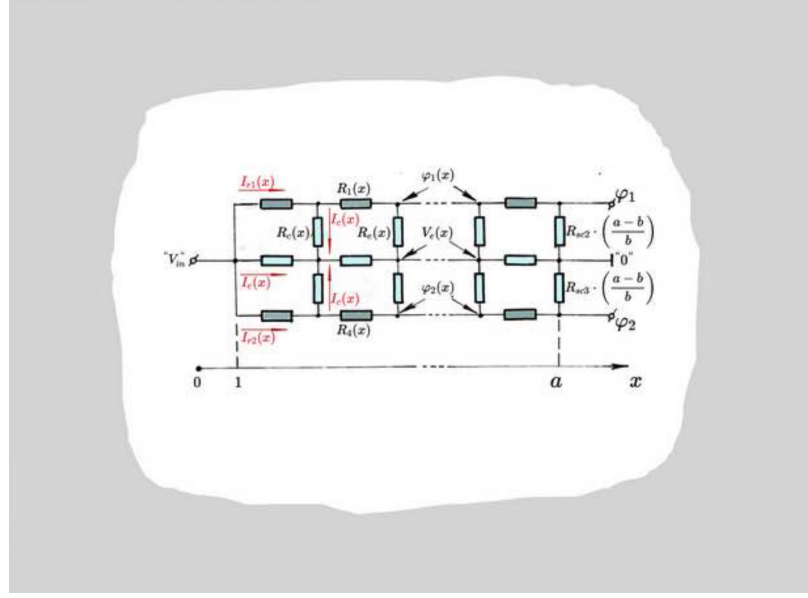


Figure 5: An equivalent diagram of the discrete analog model of the transducer in Figure 3 and Figure 4.

$$\begin{aligned}\Upsilon_1(x) &= \varphi_1(x) - V_{in}(x) \\ \Upsilon_2(x) &= \varphi_2(x) - V_{in}(x) \\ C_1 &= \left(2\sqrt{2} + \frac{R_{Sc1}}{\rho_{ee}} H_{ee}\right) \\ C_2 &= \left(2\sqrt{2} + \frac{R_{Sc4}}{\rho_{ee}} H_{ee}\right)\end{aligned}$$

The solution of the equations has the following form:

$$\Upsilon(x) = \sqrt{x} Z_1(i \cdot 2\sqrt{Cx}) \quad (14)$$

where  $Z_1(i \cdot 2\sqrt{Cx})$  is a Bessel function with an imaginary unit.

The boundary conditions used are as follows: - At  $x = 1$ :  $\Upsilon_1(1) = \Upsilon_2(1) = 0$ ,  $\varphi_1(1) = \varphi_2(1) = V_{in}$ ,  $V_{in}(1) = V_{in}$  - At  $x = a$ :  $\Upsilon_1(a) = \varphi_1$ ,  $\Upsilon_2(a) = \varphi_2$ ,  $V_{in}(a) = 0$ ,  $\varphi_1(a) = \varphi_1$ ,  $\varphi_2(a) = \varphi_2$ ,  $I_{r1}(a) = \varphi_1 \frac{b}{R_{Sc2} \cdot a}$ ,  $I_{r2}(a) = \varphi_2 \frac{b}{R_{Sc3} \cdot a}$ ,  $I_{in} = I_e(a) + 2I_c(a)$ ,  $I_e(a) = I_{in} - \varphi_1 \frac{b}{R_{Sc2} \cdot a} - \varphi_2 \frac{b}{R_{Sc3} \cdot a}$

Using the solution of the equations, the following relations for the circuit parameters were determined:

$$V_{out} = \varphi_1 - \varphi_2 = V_{in} \cdot \left( \frac{R_2}{R_1 + R_2 + \frac{R_1 \cdot R_2 \cdot b}{\rho_{ee} \cdot a} H_{ee} \cdot \Phi} - \frac{R_3}{R_4 + R_3 + \frac{R_3 \cdot R_4 \cdot b}{\rho_{ee} \cdot a} H_{ee} \cdot \Phi} \right) \quad (15)$$

$$R_{in} = \left[ \frac{1 + 2 \frac{R_2 \cdot b}{\rho_{ee} \cdot a} H_{ee} \cdot \Phi}{R_1 + R_2 + \frac{R_1 \cdot R_2 \cdot b}{\rho_{ee} \cdot a} H_{ee} \cdot \Phi} + \frac{1}{R_3 + R_4 + \frac{R_3 \cdot R_4 \cdot b}{\rho_{ee} \cdot a} H_{ee} \cdot \Phi} + \frac{b \cdot H_{ee}}{\rho_{ee} \cdot a \sqrt{2}} \right]^{-1} \quad (16)$$

In these equations,  $V_{out}$  represents the output voltage of the bridge circuit,  $V$ ;  $R_{in}$  represents the input resistance of the bridge circuit,  $\Omega$ ;  $R_1, R_2, R_3, R_4$  represents the resistance values of the electrically isolated piezoresistive channels 5, 4, 3, and 2, respectively, in the four arms of the bridge circuit,  $\Omega$ ;  $\Phi$  is a dimensionless coefficient that characterizes the strain transducer model and accounts for the redistribution of the charge carrier current in the channels and the elastic element.

We assume the following conditions:

$$\begin{aligned} R_1 = R_2 = R_3 = R_4 = R_{bc} &= \tilde{\rho}_{bc} \cdot \frac{a}{b \cdot X_j}; \\ \frac{dR_2}{d\varepsilon_x} = -\frac{dR_1}{d\varepsilon_x} = \frac{dR_4}{d\varepsilon_x} = -\frac{dR_3}{d\varepsilon_x} &= R_{bc} \cdot K_{bc}; \end{aligned} \quad (17)$$

where  $K_{bc}$  is the strain sensitivity coefficient of electrically isolated piezoresistive channels 2, 3, 4, 5. Consequently, the strain-sensitivity coefficient of the transducer and the input resistance of the bridge circuit are equal.

$$K(T, \varepsilon_y) = \frac{1}{V_{in}} \frac{dV_{out}}{d\varepsilon_y} = \frac{2K_{bc}(T)}{2 + \frac{\tilde{\rho}_{bc}(T)}{\rho_{ee}(T)} \cdot \frac{H_{ee} \cdot \Phi}{X_j}}; \quad (18)$$

$$R_{in}(T) = 2R_{bc}(T) \left[ \frac{1 + \frac{R_{bc}(T)}{\rho_{ee}(T)} \cdot \frac{H_{ee} \cdot \Phi \cdot b}{a}}{2 + \frac{R_{bc}(T)}{\rho_{ee}(T)} \cdot \frac{H_{ee} \cdot \Phi \cdot b}{a}} + 0.354 \frac{R_{bc}(T) \cdot H_{ee} \cdot b}{\rho_{ee}(T) \cdot a} \right]^{-1} \quad (19)$$

Here,  $K_{bc}(T) = K_0 + K_1 \frac{T_0}{T} + K_2 \left(\frac{T_0}{T}\right)^2$  is the strain sensitivity factor of electrically isolated piezoresistive channels 2, 3, 4, 5 with temperature dependence determined according to<sup>13</sup> by a second-degree polynomial with respect to the temperature parameter  $t = \frac{T_0}{T}$ . This relationship holds for silicon piezoresistors<sup>14</sup>.  $\alpha_{bc}[1/K]$  and  $\beta_{bc}[1/K^2]$  are approximation coefficients,  $\tilde{\rho}_{bc0}$  is the resistivity at  $T = T_0$ , and  $R_{bc}(T) = \rho_{bc}(T) \cdot \frac{a}{b \cdot X_j} = R_{bc0} \left[1 + \alpha_{bc}(T - T_0) + \beta_{bc}(T - T_0)^2\right]$  represents the resistance value of electrically isolated piezoresistive channels 2, 3, 4, 5.  $R_{bc0}$  is the resistance at  $T = T_0$ , and  $\rho_{ee}(T) = \rho_{ee0} \left[1 + \alpha_{ee}(T - T_0) + \beta_{ee}(T - T_0)^2\right]$  is the resistivity of the initial silicon wafer 7 with a temperature dependence defined by a second-degree polynomial.  $\alpha_{ee}[1/K]$  and  $\beta_{ee}[1/K^2]$  are approximate coefficients.

In some transducer designs, the condition  $a \leq H_{ee}$  may hold. In such cases, assuming a uniform current distribution in the elastic element along the  $Z$  direction would not accurately reflect the actual distribution in the real object. Thus, instead of  $H_{ee}$ , its effective value  $H_{ef}$  is used. The redistribution parameter of the charge carrier current in the channels and the elastic element in this case is given by:

$$\Lambda = \frac{H_{ef} \cdot \Phi \cdot b}{a}. \quad (20)$$

The numerical value of the parameter  $\Lambda$  can be determined by joint measurements<sup>15</sup>. With the knowledge of the temperatures within the selected operating range  $T_1$  and  $T_2$ , the values of  $R_{inT_1}$  and  $R_{inT_2}$  are measured. Consequently, the values  $R_{bcT_1}$  and  $R_{bcT_2}$  are calculated for the same temperature values. If the values of  $\alpha_{bc}$  and  $\beta_{bc}$  are unknown before,  $R_{bcT_1}$  and  $R_{bcT_2}$  are measured on specifically designed test samples. The same procedure is followed for  $\rho_{eeT_1}$  and  $\rho_{eeT_2}$ . Using the system of two equations derived from Equation (19), we can obtain the ratio to calculate  $\Lambda$  (Equation 11).

The relationship between the parameter  $\Lambda$  and the resistivity  $\rho_{ee}$  was determined by measuring test samples with a thickness of  $H_{EE} = 1 \cdot 10^{-2}$  cm. The variation in  $\Lambda$  values for  $\rho_{ee}$  ranging from 0.5 to 10  $\Omega \cdot \text{cm}$  was within the measurement error. For test samples where piezoresistive channels were formed by implantation of boron ions with a doping dose of  $2 \cdot 10^{15} \text{ cm}^{-2}$ ,  $\Lambda = (9.1 \pm 0.5) \cdot 10^{-3}$  cm.

The unification of the sensor design based on the input mechanical quantities is achieved by adjusting the slope of the conversion characteristic by selecting the thickness of the elastic element. An important requirement is that the circuit parameters remain independent of the thickness  $H_{ee}$ . From the experimental dependence shown in Figure 6, which illustrates the change in input resistance  $R_{in}$  as a function of the calculated parameter  $\frac{H_{ee}}{a}$ , it can be observed that this condition is satisfied when  $\frac{H_{ee}}{a} \geq 0.3$ .

The permissible limit of the complementary temperature error of the transducer, denoted  $\Gamma_{kt}$ , is determined by the geometric sum of the errors arising from the variation in the strain sensitivity

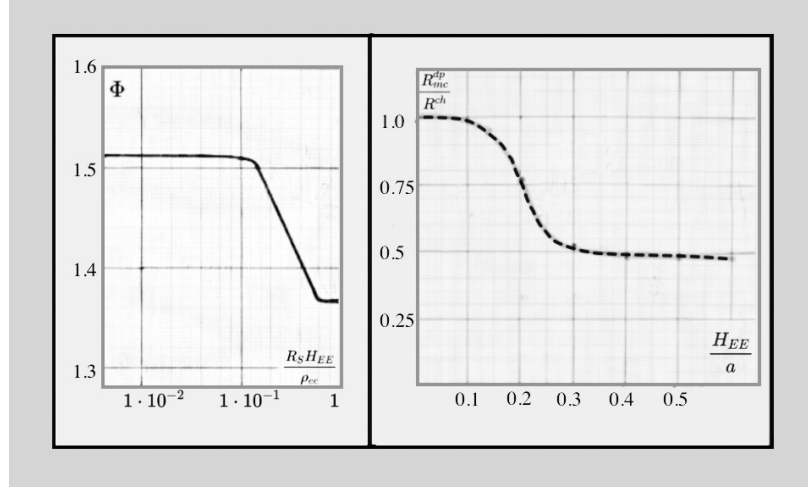


Figure 6: Experimentally obtained dependences of variation of coefficient  $\Phi$  and input resistance on design parameters of the transducer with distributed parameters.

coefficient of the transducer with respect to the initial temperature  $T_0$  as the temperature changes within the operating range. Mathematically, it is expressed as follows:

$$\Gamma_{kt} = \frac{1}{K_0} \sqrt{\frac{1}{n-1} \sum_{i=0}^n \left[ \frac{K - K_0}{(T_2 \frac{n-i}{n} + T_1 \frac{i}{n} - T_0)} \right]^2} \quad (21)$$

Finally, considering the relation (18), the temperature dependence of the parameters in (18) and the value of the parameter  $\Lambda$  determined through Equation (20), we obtain the expression (10) for  $\Gamma_{kt}$ .

## 4 Manufacturing Samples of Small-Size Silicon Mechanical Sensors

To manufacture a silicon resistor integral pressure differential transmitter with the specified specifications, the following design and material parameters are chosen:

- Pressure range:  $0 \div 0.06$  MPa.
- Margin of admissible basic error: +1%.
- Operating temperature range:  $+50^\circ\text{C} - +250^\circ\text{C}$ .
- Power supply voltage: 6 V.
- Permissible additional temperature error  $\Gamma_{kt} = 0.06 \text{ } \%/^\circ\text{C}$  <sup>16</sup>.

The selected sensor design consists of a silicon membrane with a thickness of  $H_{ee} = 1 \times 10^{-2}$  cm. Square contact areas (6, 9, 10, 11) have side dimensions  $b = 2 \times 10^{-3}$  cm and are connected to each other by four ion-doped single-band piezoresistive channels (2, 3, 4, 5) of type p. These channels have a width of  $b = 2 \times 10^{-3}$  cm and are oriented along the crystallographic direction [011]. The coefficients  $\alpha_{bc}$  and  $\beta_{bc}$  were determined for the range  $\tilde{\rho}_{bc} = (5 \times 10^{-3} \div 5 \times 10^{-2}) \Omega \cdot \text{cm}$  in the temperature range  $-60^\circ\text{C} - +170^\circ\text{C}$ .

For silicon wafers, initial wafers doped with the KDB-0.5, KDB-1.0, and KDB-10 boron types ( $\rho_{ee}(25^\circ\text{C}) = 0.5, 1, 10 \Omega \cdot \text{cm}$ ) were chosen. The temperature dependence of resistivity for silicon

wafers does not decrease dramatically until the intrinsic conductivity temperature. According to <sup>17</sup>, within the temperature range  $50^{\circ}\text{C} \div 250^{\circ}\text{C}$  ( $323\text{ K} \div 523\text{ K}$ ), it is determined by:

$$\rho_{ee}(T) = 2.2 \left[ 1 + 5.3 \times 10^{-3}(T - 423) + 8.2 \times 10^{-6}(T - 423)^2 \right] \text{ } [\Omega \cdot \text{cm}]$$

The experimental measurements provided the dependence of the parameter  $\Lambda$  on the average resistivity  $\tilde{\rho}_{bc}$  and the doping depth  $X_j$  during the formation of piezoresistive boron ion implantation channels. For the specified doping parameters (80 keV energy, doping dose  $2 \times 10^{15}\text{ cm}^{-2}$ , average resistivity  $\tilde{\rho}_{bc} = 7.3 \times 10^{-3}\text{ } \Omega \cdot \text{cm}$ , alloy depth  $X_j = 0.86 \times 10^{-4}\text{ cm}$ ), the input resistance values of the transducer at temperatures  $T_1 = 323\text{ K}$  and  $T_2 = 598\text{ K}$  are  $R_{in1} = 338\text{ } \Omega$  and  $R_{in2} = 598\text{ } \Omega$ , respectively. The temperature dependence of the strain sensitivity coefficient  $K_{bc}(T)$  and resistivity  $\tilde{\rho}_{bc}(T)$  in the temperature range  $50^{\circ}\text{C} \div 250^{\circ}\text{C}$  is given by the following relationships:

$$K_{bc}(T) = 10 + 60 \frac{423}{T} - 14 \left( \frac{423}{T} \right)^2 ;$$

$$\tilde{\rho}_{bc}(T) = 8 \times 10^{-3} \left[ 1 + 1.1 \times 10^{-3}(T - 423) + 1.5 \times 10^{-6}(T - 423)^2 \right] \text{ } [\Omega \cdot \text{cm}]$$

The parameter value  $\Lambda = 2.67 \times 10^{-3}\text{ cm}$  and the complementary temperature error of the sensor  $\Gamma_{kt} = 0.0386\text{ } \%/^{\circ}\text{C}$ .

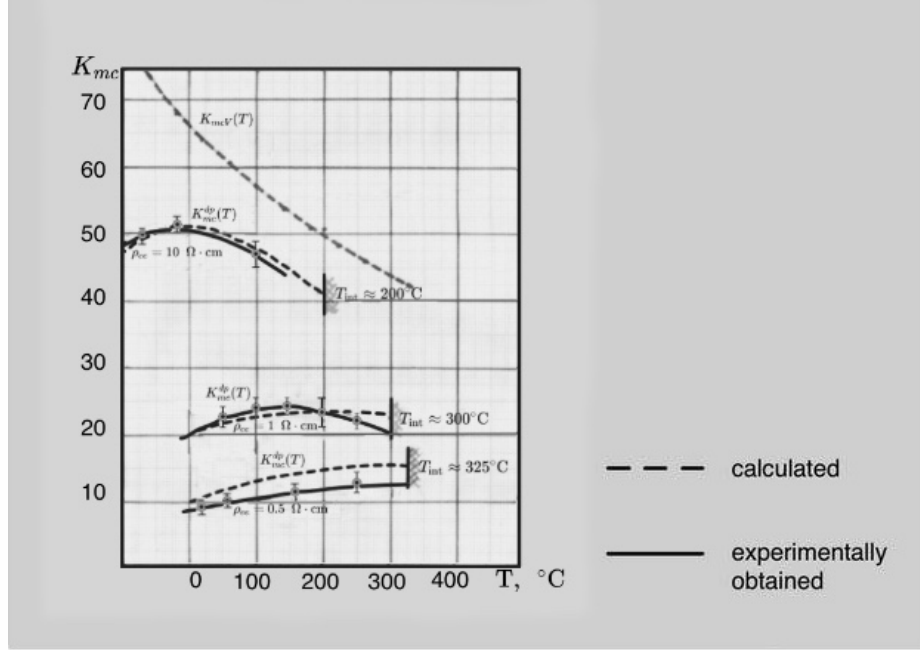


Figure 7: Calculated and experimentally obtained temperature changes of strain-sensitivity coefficients for transducers with distributed parameters and electrically isolated from the elastic element.

Figure 7 shows the calculated and experimentally obtained temperature variations of the strain sensitivity coefficients for transducers with distributed parameters ( $K_{bc}^{dp}(T)$ ) and electrically isolated from the elastic element ( $K_{bc}^{bcV}(T)$ ). In the case of the small sensor design, the design chosen with distributed parameters and  $\rho_{ee} = 1\text{ } \Omega \cdot \text{cm}$  showed a parameter value of  $\gamma_{mc} = 0.04\text{ } \%/^{\circ}\text{C}$  in the temperature range of  $(0 \div +300)^{\circ}\text{C}$ , determined experimentally.

For the temperature range of  $(0 \div 325)^{\circ}\text{C}$ , the variant with  $\rho_{ee} = 0.5\text{ } \Omega \cdot \text{cm}$  was investigated. In this case, the error is determined by the value of  $\gamma_{mc} = 0.08\text{ } \%/^{\circ}\text{C}$  (Figure 7).

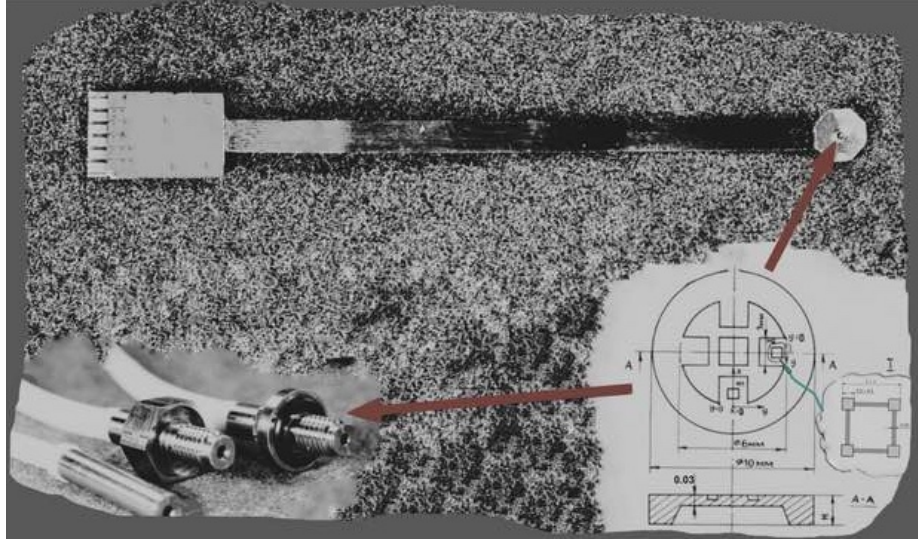


Figure 8: Static-dynamic pressure sensor

## 5 Conclusions

Figure 8 illustrates a static-dynamic pressure sensor with a pressure range from  $0 \div 0.01$  MPa to  $0 \div 1$  MPa. The sensor has compact overall dimensions of  $\varnothing 13 \times 11$  mm and weighs less than 10 g. It incorporates a monolithic transducer with distributed parameters, without insulating p-n junctions. The sensor exhibits an intrinsic error of less than  $\pm 1\%$  and a complementary temperature error of less than  $0.05\%/^{\circ}\text{C}$  within the temperature range of  $0 - 300^{\circ}\text{C}$ .

These technical characteristics met the requirements for elements used in control, monitoring, and regulation systems, as well as for final product testing at the Ministry of General Machine Building (in the USSR) at that time.

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